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Colour cameras:
variation of colour analysis with change of angle of incidence on to the colour splitter (dichroic tilt)

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Page 9, Fig. 8 Legend: for 'red channel' read 'green channel'

for 'green channel' read 'red channel'

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Research Report No. T-156
(1965/49)

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SUMMARY

Dichroic tilt, that is, variation in colour analysis over the optical image field, has been investigated for one type of prism-block colour analyser. Optical results are compared with those deduced from waveform measurements on a colour television camera. The observed dichroic tilt is found to be due to two causes, one of which is fundamental to multilayer dielectric filters, the other is due to a slight non-uniformity of dielectric coating.

A determination of the threshold of sensitivity of a human observer to dichroic tilt is described and a recommendation is made for a specification of dichroic tilt in colour analysis blocks used in colour cameras.

1. INTRODUCTION

In a colour television camera, it is essential that light from the scene shall be analysed into appropriate red, green and blue components. Of the various methods of analysing light into spectral bands, multilayer dielectric interference filters offer the most efficient method known at present. Although a high efficiency is achieved by this method, there are two disadvantages, namely, polarization effects[1] and variations in the colour balance over the optical image field, due to variations in the angle of incidence on to the filters, usually known as 'dichroic tilt'. This report describes an investigation into the latter effect. The change of colour balanced in the displayed picture may be either from top to bottom (as in Philips' three-plumbicon colour cameras), or from side to side (as in the three image-orthicon colour cameras used by the BBC), according to the orientation of the colour splitter. The effect is fundamental to an interference filter and arises mainly because the optical path difference in a layer is a function of the angle of the ray in the layer (Fig. 1).

$$\text{Path difference} = 2\, n_1 e \cos\theta$$

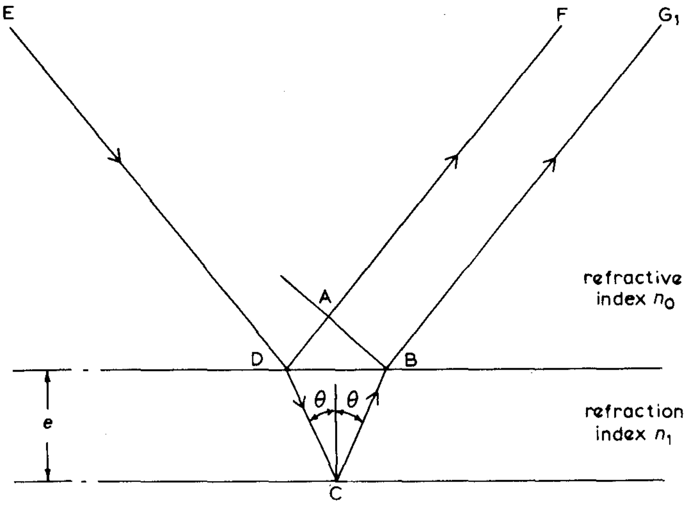
$$\text{Phase difference} = \frac{2\pi}{\lambda} \cdot 2\, n_1 e \cos\theta + \phi$$

where n_1 = refractive index of the layer
e = thickness of layer
θ = angle of ray in the layer
λ = wavelength (in vacuo)

Fig. 1 - Illustrating interference by a thin film

Path difference = (DC + CB) in index n_1 - DA in index n_o = $2n_1 e\cos\theta$

Legend:
ED = incident ray
DAF = directly reflected ray
DCBG = ray reflected at second interface
θ = angle of reflection (in index n_1)
e = thickness of thin film



and ϕ is determined by the phase changes occurring on reflection and refraction. It is usually equal to π in practical cases.

In a multilayer dielectric filter the principal effect on changing from normal incidence to (say) 45° is to cause a general shift in wavelength of the mean reflectance (or transmittance) curve, together with a separation of the curves for the two components of polarization. An example of this is shown in Fig. 2. A subsidiary effect is a slight change of level of the mean reflection (or transmission) curve.

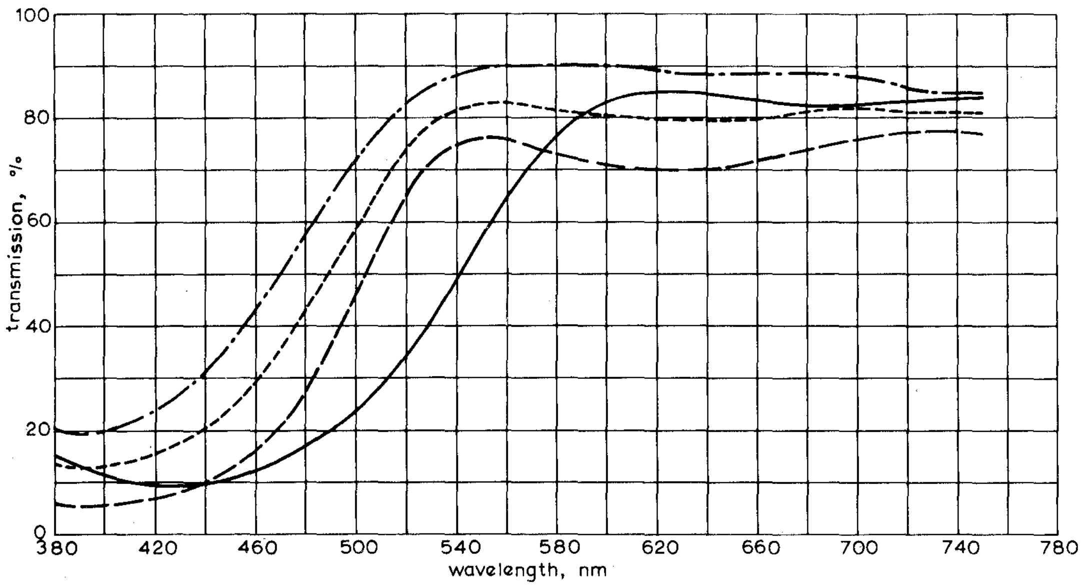


Fig. 2 - Transmission characteristics of a blue-reflecting dichroic mirror at 0° and 45°

——— curve for 0° angle of incidence
------- mean curve for 45° angle of incidence
— — — perpendicular component for 45° angle of incidence
—·—·— parallel component for 45° angle of incidence

A colour television splitting system usually has two dichroic mirrors (inclined in opposite directions) one of which, for example, reflects red light and the other reflects blue. A suitable change in angle of inclination of the incoming rays will cause the transmission curve at the short wavelength side of the green channel to move to shorter wavelengths, the longer wavelength curve will then move in the opposite direction (i.e. to longer wavelengths) because it is controlled by the other dichroic mirror (viz. the red-reflect mirror) which is inclined in the opposite sense. Hence, the green channel will tend to maintain constant mean wavelength but will alter its bandwidth as the angle changes. If the sides of the green transmission curve are controlled primarily by shaping filters, rather than by the dichroics themselves, then the tilt will be minimised, but with some overall loss of efficiency. As far as the blue and red channels are concerned, variations in the angle of inclination of the incoming rays will tend to move the whole of spectral curve in one direction only. Hence, the mean wavelength will change although the optical bandwidth may remain approximately constant. In the colour camera, what finally matters are the signal currents produced by the camera tube in the R, G, and B channels and, for a very small lens aperture and for a tube operating in a linear mode, these are given by:

$$I = \int E(\lambda) \,.\, S(\lambda) \,.\, T(\lambda) \,.\, R(\lambda) \,.\, L(\lambda) \,.\, d\lambda \qquad (1)$$

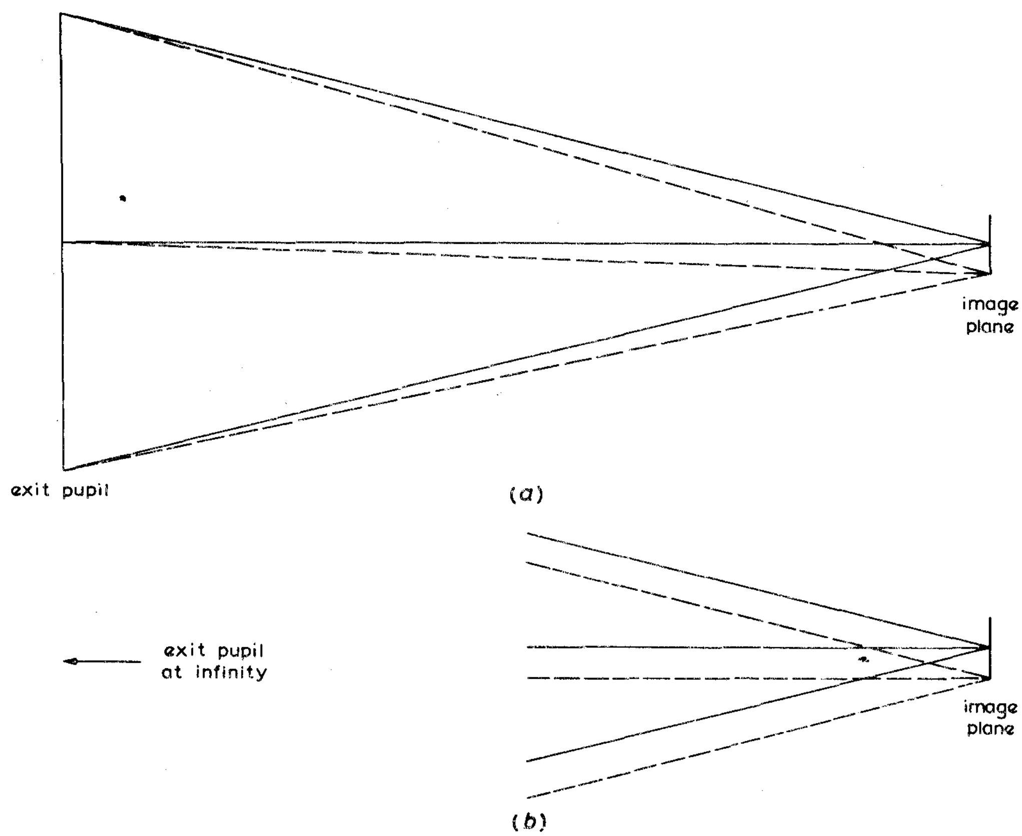


Fig. 3 - Showing rays to centre and bottom of image for

(*a*) an exit pupil 180 mms from image plane
(*b*) an exit pupil at infinity (telecentric system)

where I = signal current
$E(\lambda)$ = energy distribution of light source
$S(\lambda)$ = spectral sensitivity of camera tube
$T(\lambda)$ = spectral transmission curve of R, G or B channel for the angle of inclination corresponding to that part of the image being considered
$R(\lambda)$ = reflectance curve of colour being observed
$L(\lambda)$ = spectral transmission of lens

To extend this formula to a finite lens aperture a further (two dimensional) integration is necessary to take into consideration the cone of rays which go to form each image point, since the angle of incidence on the layers will vary over this cone. (See Section 3.2.)

The range of angles of incidence is controlled by the size and position of the exit pupil in relation to the image size and position. For this reason it is preferable to have the exit pupil as far away from the image as possible. A telecentric system (with its exit pupil at infinity) would in principle avoid dichroic tilts: the possible disadvantages of a telecentric system are (i) increase in any effects due to non-uniformity of coating due to the scanning action of the image-forming beam and (ii) need for larger optical elements (both splitter prism and lens elements) if vignetting is to be avoided. Fig. 3 illustrates the image forming cone of rays for a normal and a telecentric system.

2. OPTICAL MEASUREMENTS ON A PLUMBICON BLOCK

Although the comments made in the introduction are of general validity, the detailed results which are about to be presented relate to one particular type of colour analysis system as used with plumbicon colour cameras and described by de Lang and Bouwhuis.[2] These authors are well aware of the difficulties which are inherent in the use of dichroic prism-block assemblies. They have considerably reduced the polarization effects in this particular block by the use of three-quarter-wavelength high-index layers together with quarter-wavelength low-index layers. The result is shown in Fig. 4 which gives the transmissions for the two polarization components for normal incidence. No further comments will be made about polarization effects and all the remaining results will quote transmission to unpolarized light.

By the use of the three-quarter-wavelength high-index layers and quarter-wavelength low-index layers together with a reduction of the angles of incidence at the red- and blue-reflecting layers in the block to the low values of 13° and 25·5° respectively, the changes in transmission characteristic with change of angle of incidence have been made fairly small. Figs. 5, 6 and 7 show the transmission characteristics of the R, G and B channels respectively for three angles of incidence.

These measurements were made using a Unicam SP.500 Spectrophotometer. In the case of the green channel, no difficulty arises in that the emerging beam is parallel to and colinear with the incident beam. For the red and blue channels, a mirror was used to redirect the light beam and results were corrected for the known reflectance of the mirror. Additional checks were performed by moving the photocell box to receive the directly emerging light from the red and blue channels, although this is a somewhat less convenient method of operating the spectrophotometer. In

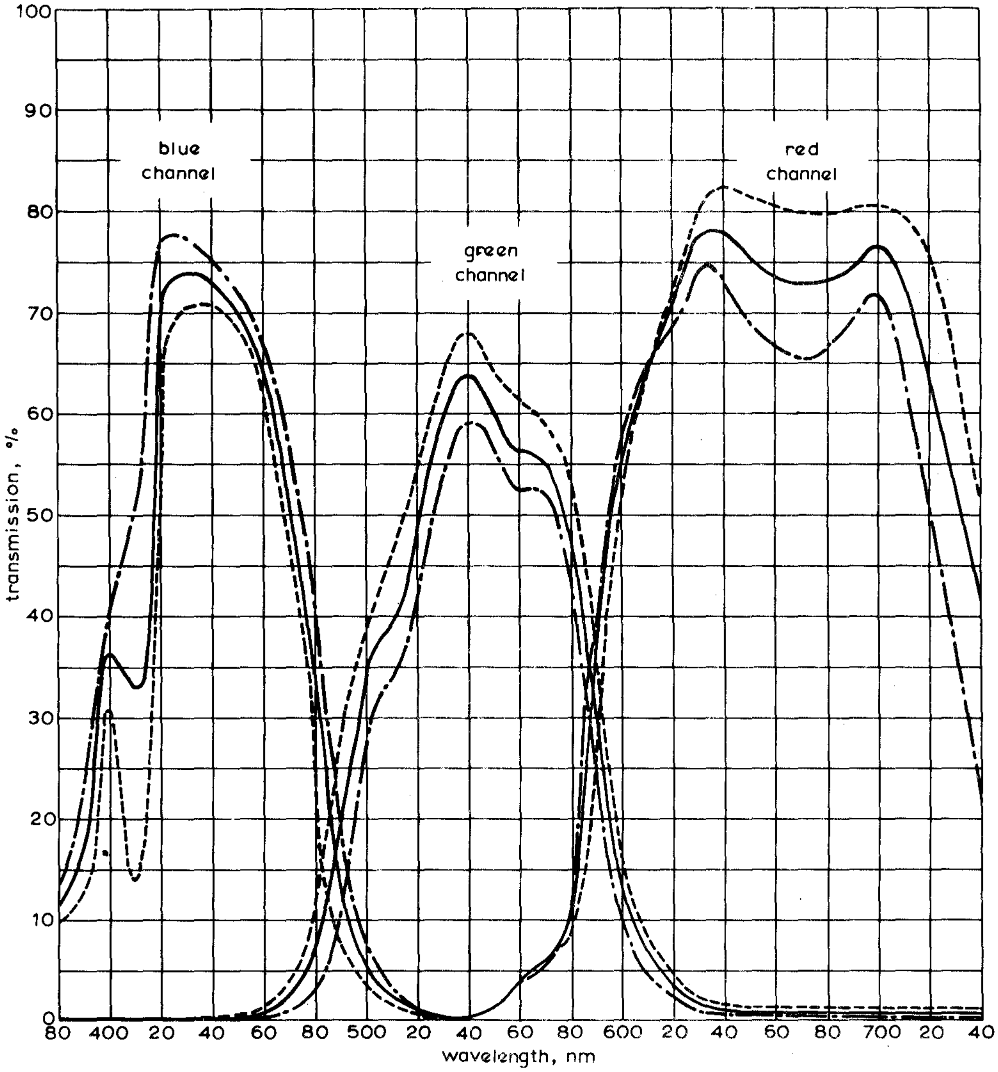


Fig. 4 - Transmission characteristics of a prism block

------ parallel component —— —— perpendicular component ———— mean curve

one case, the change in angle of incidence of the principal ray to the top centre of the field to the principal ray to the bottom centre is about ± 2° (see Fig. 3(*a*)). When the Angenieux 10 × 18E lens* is used at full aperture the cone of rays about the central image point has a semi-angle of about 13°. Thus, if the whole aperture and whole field of view are taken into account the range of angles over which rays enter the prism block is ± 15° (in the vertical plane through the central optical axis). The variations in transmission characteristic over this range are not negligible as may be inferred from Figs. 5, 6 and 7 but it should be remembered that the dichroic tilt effect is due to a change of angle of about ± 2°. There will also be a change of balance when the aperture is changed.

* This lens has been manufactured specifically for the Philips colour camera.

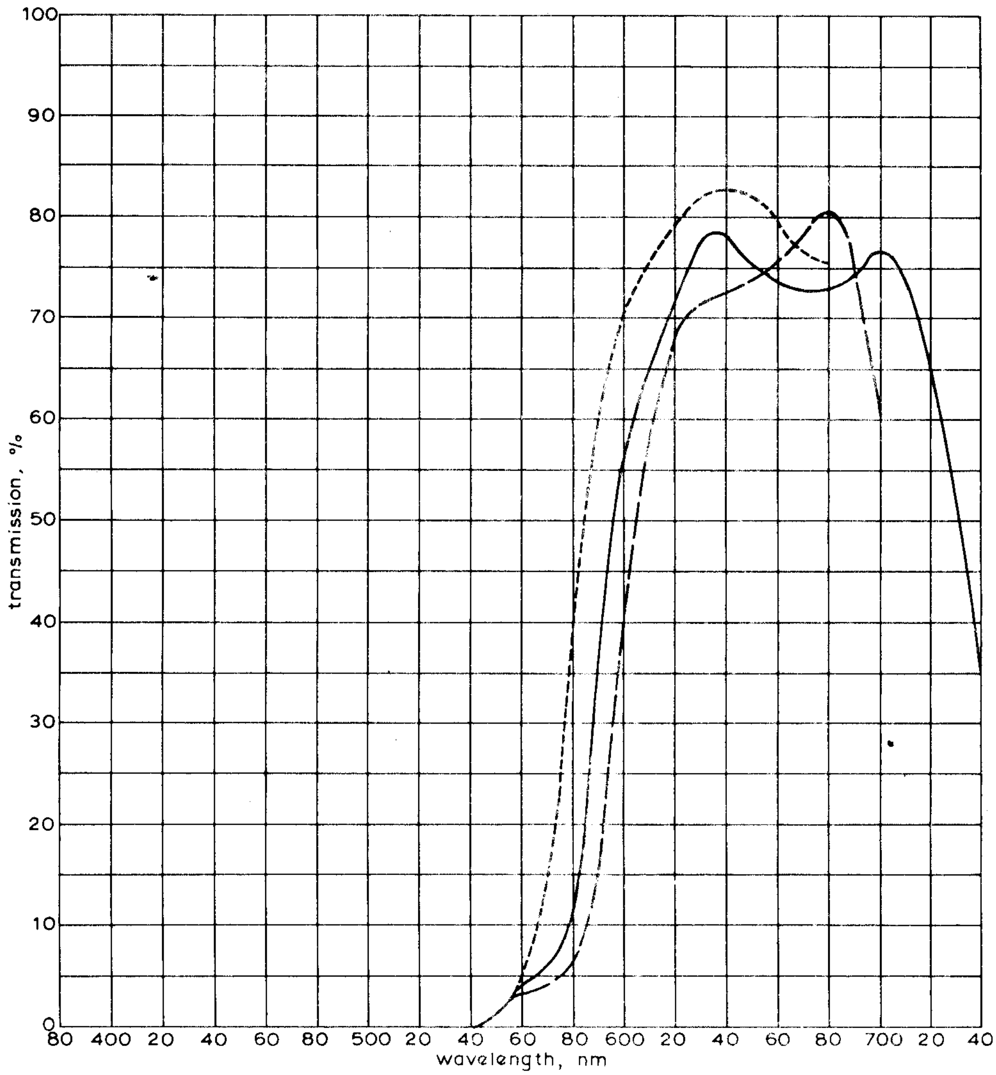


Fig. 5 - Transmission of the red channel for three angles of incidence

Angles of incidence

——— 0° - - - - - - - -9° — — — +9°

3. COMPUTED OUTPUTS OF THE R, G AND B CHANNELS

3.1. Outputs in the Case of a Small Relative Aperture

The optical transmissions as measured in Section 2 are used in the manner described in the introduction to compute the signal currents to be expected from three plumbicon camera tubes. The spectral sensitivity curve used in the calculation was the one quoted in BBC Research Department Report No. T-126. The colour used [$R(\lambda)$ in equation (1)] is assumed to be a white with a uniform reflectance throughout the spectrum. $E(\lambda)$ is chosen as a total radiator at 3000°K. For a small relative aperture, no integration is performed to take into consideration the finite cone of rays and equation (1) is used. The results of these summations are shown in Fig. 8: it has been assumed that the gains of amplifiers would be adjusted so that the outputs

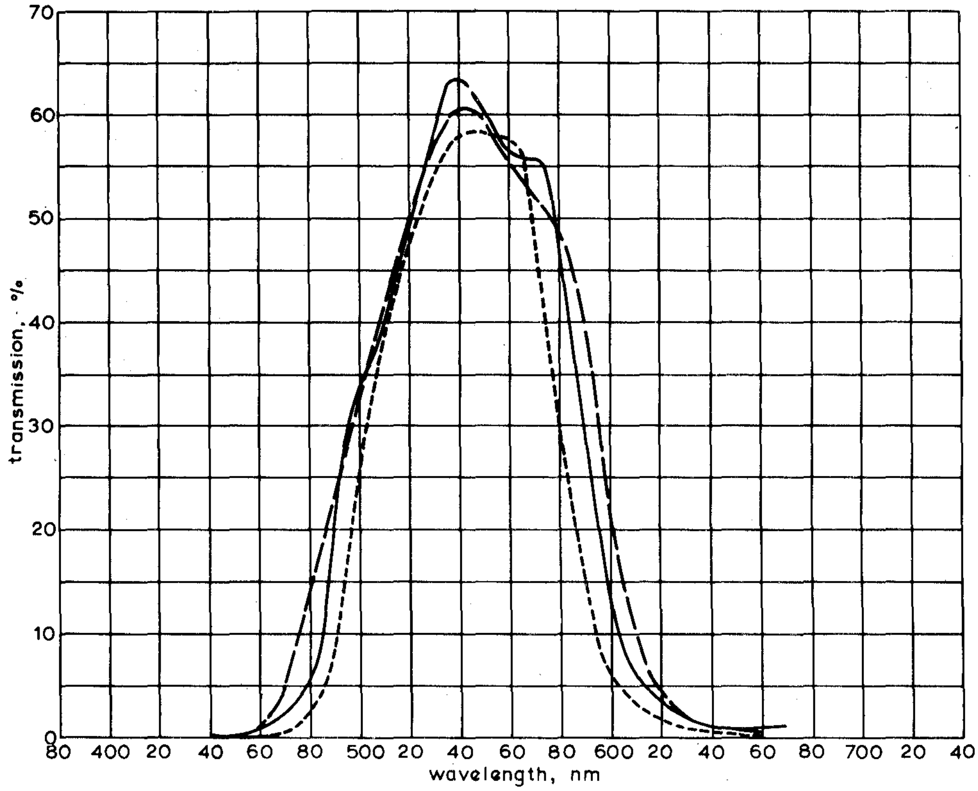


Fig. 6 - Transmission of green channel for three angles of incidence

Angles of incidence

——— 0° - - - - -9° — — —+9°

at the centre of the field (0°) would be unity in each channel. The curves shown in Fig. 8 should also correspond to the measured outputs from the R, G and B channels of a camera when used with a small lens aperture since the vignetting of a zoom lens should be negligible under these conditions (say f/16). Section 4 gives a comparison between signal outputs measured on a waveform monitor and optically computed outputs.

3.2. Outputs for Apertures up to the Maximum Value

The output corresponding to one angle of incidence is given by equation (1). For a cone of semi-angle θ_0 it is necessary first to evaluate an annulus between θ and $\theta + d\theta$ and then to integrate from 0° to the appropriate cone angle θ_0. One experimental difficulty is that the measurements have been taken only in one principal plane (viz. the vertical plane, as used in the plumbicon colour camera) and ideally measurements should be taken in a representative number of planes. An approximate interpolation was used, which is illustrated in Fig. 9. Having obtained the output for an annular cone of rays, the final summation assumes that the weighting of each annulus is proportional to θ*.

There are two aspects of these results which are of particular interest (i) changes in colour balance at the centre of the field upon changing the aperture of the lens (ii) changes in the colour tilt from top to bottom of the field with change of aperture.

* This ignores a $\cos\theta$ correction for angle of incidence on to the image plane. In view of the approximate nature of the data and the fact that the largest θ is 15°, this omission has only a slight effect on the result

Dealing first with (i), chromaticities have been computed for the change in white point at the centre of the field and the results are shown in an enlarged version of the 1960 CIE-UCS diagram which relates to the vicinity of the white point, (Fig. 10). Commencing with an aperture of f/16 and normalizing the outputs to give 1 : 1 : 1 on the three channels, the monitor is adjusted to give Illuminant C. The effect of opening up the lens is shown (Fig. 10) to give a shift predominantly in the red-magenta direction. The magnitude of the shift is not unduly large and in fact amounts to just over 1 'just-noticeable difference' (jnd) (MacAdam data)[3]* for a change in aperture from f/16 to f/2·2. Electronic measurements on this subject are reported in Section 4.

The results relating to the second item (ii) can be expressed in jnds of colour change from top to bottom of the field and are given in Table 1.

The tilts are in the direction green-cyan to red-magenta from the top to the bottom of the field.

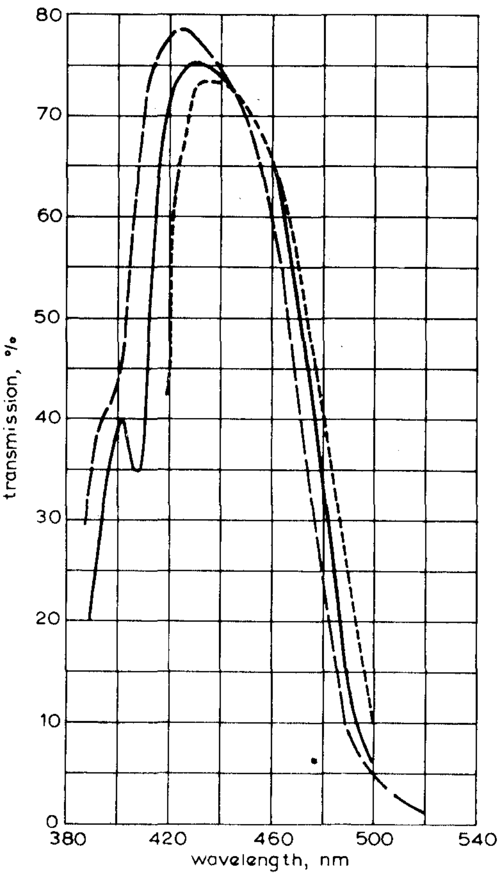


Fig. 7 - Transmission of the blue channel for three angles of incidence

Angle of incidence

——— 0° — — — -9° - - - - - +9°

4. COMPARISON WITH RESULTS DERIVED FROM WAVEFORM MEASUREMENTS

During the period 9th to 21st December 1964, a plumbicon colour camera was made available to the BBC and fairly extensive measure-

TABLE 1

APERTURE	COLOUR TILT IN JNDS
f/16	0·9
f/11	0·9
f/8	1·2
f/5·6	1·2
f/4	1·3
f/2·8	1·2
f/2·2	1·0

* Strictly speaking, the MacAdam experiments give the standard deviation (σ) of colour matching trials with an additive colorimeter. We have assumed that $3\sigma = 1$ jnd.

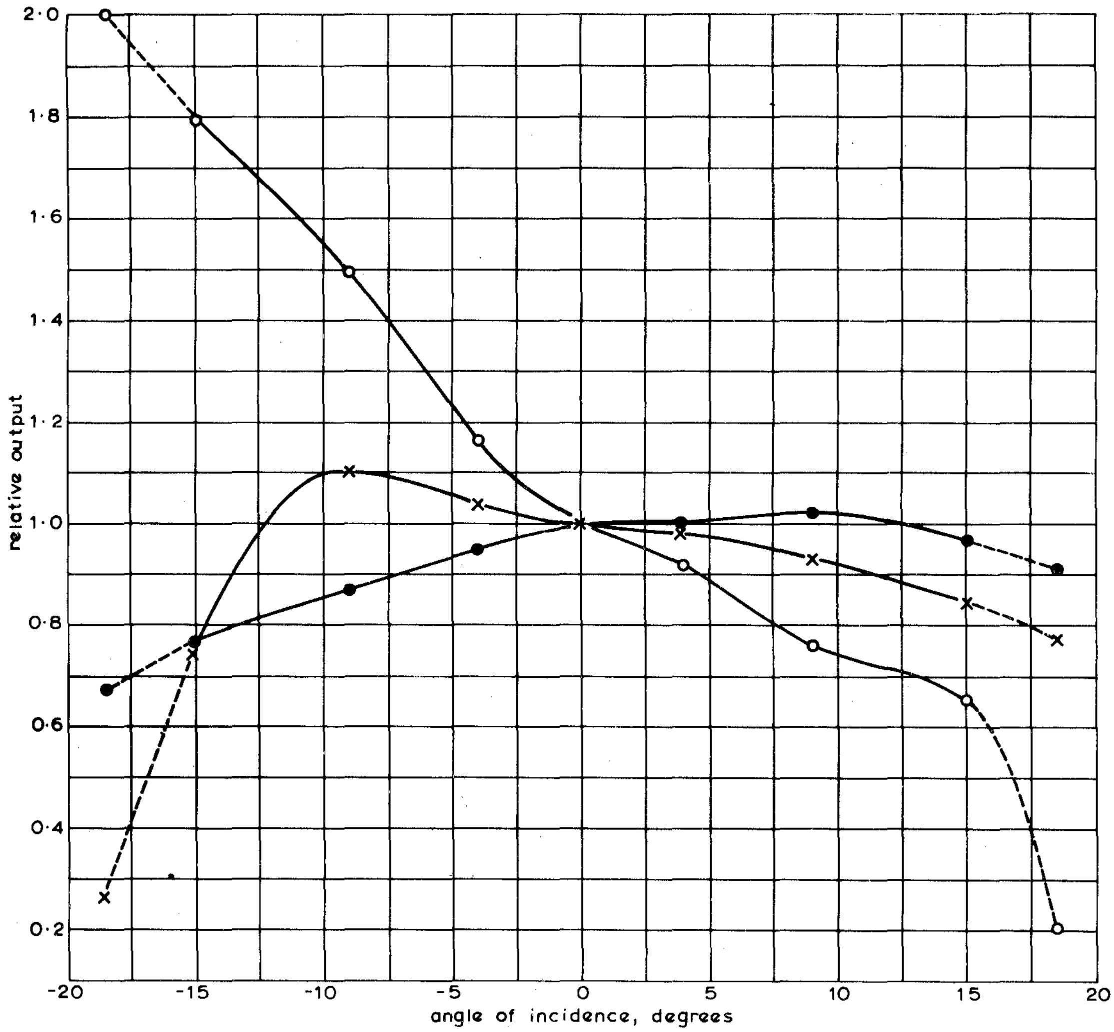


Fig. 8 - Calculated outputs of the channels for a very narrow angular pencil of light

(The values at ± 18½° are outside the range of angles for which the prism block is intended to work)

●—●—● red channel ×—×—× blue channel o—o—o green channel

ments on colour tilts were made as part of the programme of work. The measurements consisted of observing output voltages (as displayed on a waveform monitor) in the R, G, and B channels corresponding to various positions of the field scan when the camera was observing a uniformly rear illuminated sheet of flashed opal. The camera channel gain controls were not altered during a complete series of measurements: variations in lens aperture were compensated by altering the distance of a 2 kW spot light used to illuminate the opal screen. At its nearest distance (corresponding to f/16) the lamp was about 7 ft (2·14 m) away from the opal screen. In order to ensure uniformity of field only a small central fraction of the area illuminated by the spot lamp was used to illuminate the opal glass.

Measurements were made to determine (a) variation of colour balance at the centre of the field corresponding to changes of lens aperture (b) variations in tilt from top to bottom of field as a function of lens aperture.

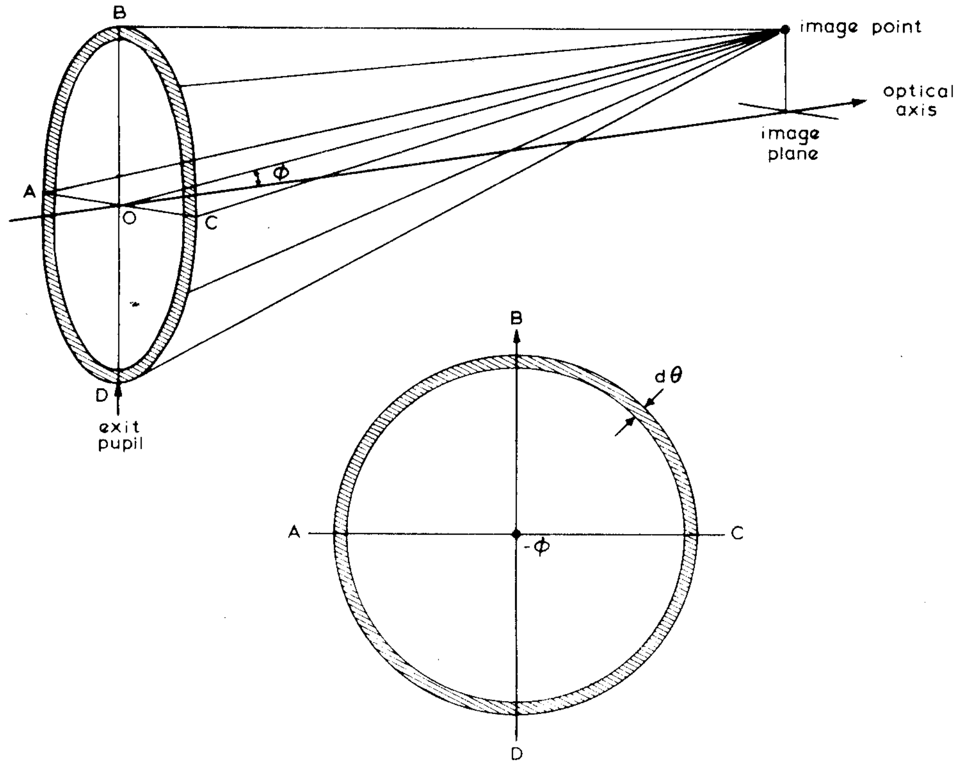


Fig. 9 - Illustrating the approximate evaluation of the signal from a cone of rays of semi-angle θ

For integration over the shaded annulus mean value is assumed to be mean of the values at A, B, C and D. Values at B and D are measured. Values at A and C assumed to be the same as the value at 0

The measurements on variation with aperture of colour balance at the centre of the field showed only small changes in the relative values of R, G and B and most of the variations observed were within the experimental accuracy of measurement. The maximum variation from the mean values (averaged for all apertures) corresponded to about 0•5 jnd in the green direction and was observed at f/8. This is not inconsistent with results given in Section 3.2 and shown graphically in Fig. 10. Detailed agreement with Fig. 10 at each aperture is not found: this would have needed an accuracy of measurement of about ± 0•2%, which is not attainable using waveform monitors.

Measurements of dichroic tilts were made over the field at seven stops, from f/2•2 to f/16. At f/16 it was possible to make accurate measurements at the beginning of the field scan (i.e. 0/9ths) and at intervals of 1/9th field scan up to the full scan. At full aperture (f/2•2) and at apertures of f/2•8, f/4, f/5•6, f/8 and f/11 waveform measurements were made at 2/9, 4/9, 6/9, 8/9 and 9/9 of the field scan. The waveform at the commencement of the scan (0/9) was disturbed for some unknown reason and it was impossible to read off the magnitude with sufficient precision. These waveform measurements can be interpreted as chromaticity shifts. Alternatively, if the vignetting characteristics of the zoom lens (10 × 18E) are known, the optical measurements can be used to compute the expected waveforms over the field.

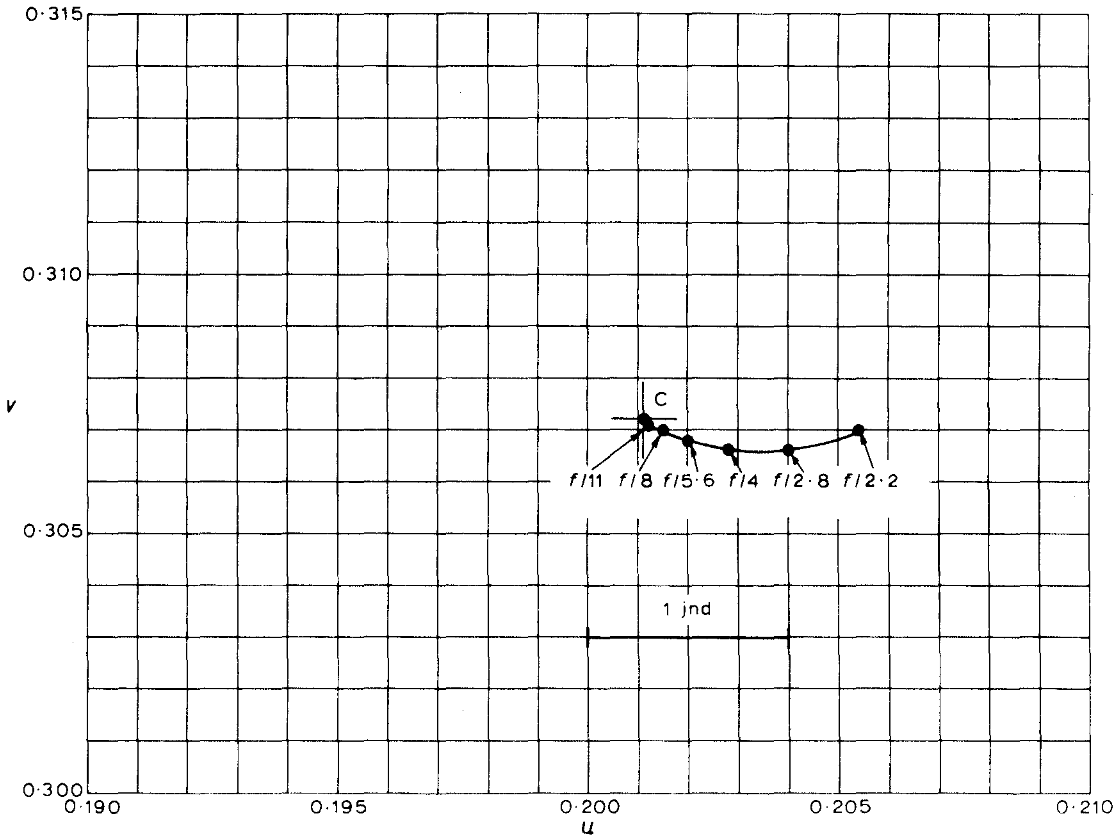


Fig. 10 - Calculated variation of colour balance with aperture at centre of field

Colour balance set to Illuminant C at f/16

Dealing first with the computed chromaticity shifts, one way of attempting to overcome the limited accuracy of individual waveform measurements is to consider the whole set of results (Table 2). If each channel is considered at one field position, variations of the channel output with aperture are seen to undergo fairly systematic changes. For example, take the G output at 2/9 field position: Table 2 shows values of •924, •967, •985, 1•003, •985, •984, •981.

TABLE 2

FIELD POSITION	0/9	1/9	2/9	3/9	4/9	5/9	6/9	7/9	8/9	9/9	CHANNEL	APERTURE
			•883		1•00		1•00		•814	•764	R	
			•924		1•01		•975		•84	•753	G	f/2•2
			•885		1•003		•987		•87	•78	B	
			•922		•987		1•037		•954	•906	R	
			•967		1•003		•985		•910	•855	G	f/2•8
			•94		•996		1•017		•979	•941	B	
			•912		•995		1•06		•978	•978	R	
			•985		1•004		•985		•93	•913	G	f/4
			•929		1•00		1•00		•965	•947	B	

FIELD POSITION	0/9	1/9	2/9	3/9	4/9	5/9	6/9	7/9	8/9	9/9	CHANNEL	APERTURE
			·921		·995		1·025		·995	·98	R	
			1·003		1·003		·985		·937	·92	G	f/5·6
			·95		1·00		1·00		·983	·966	B	
			·927		·994		1·028		·994	·977	R	
			·985		1·004		·985		·947	·928	G	f/8
			·941		1·00		1·00		·980	·961	B	
			·902		·993		1·029		·993	·975	R	
			·984		1·004		·984		·963	·963	G	f/11
			·904		1·004		·984		·964	·964	B	
	·803	·836	·885	·951	·984	1·016	1·00	·984	·967	·918	R	
	·924	·944	·981	·981	1·00	1·00	·981	·944	·925	·887	G	f/16
	·830	·849	·906	·925	·981	1·019	·981	·944	·925	·887	B	

Apart from the value 1·003 which would appear to be spuriously high, there appears to be a maximum value of about ·985. All channels show this behaviour towards either top or bottom of the field, viz. an initial increase followed by a quasi-steady maximum and then followed by a decrease at f/16. The maximum values are considered to be as in Table 3.

TABLE 3

FIELD POSITION	2/9	4/9	6/9	8/9	9/9
R	·925	·995	1·028	·994	·980
G	·985	1·004	·985	·950	·930
B	·95	1·002	1·000	·980	·963

These maxima are achieved in the aperture range of f/4 to f/11. The chromaticities deduced from the *R*, *G* and *B* values given in Table 3 are shown in Fig. 11 and these are considered to be the most reliable general estimates that can be made from the experimental data. The chromaticities calculated from optical data for an aperture of f/5·6 to f/8 are also shown in Fig. 11. Bearing in mind that the scale of Fig. 11 permits a change of 1 part in 2000 in the *uv*-coordinates to be seen easily, the agreement at 6/9, 8/9 and 9/9 of the field is considered to be fairly satisfactory. The 'agreement' for 2/9 field is considered to be unsatisfactory. Some factor not previously considered must be causing the relatively poor agreement in the upper half of the field.

At f/16 a more detailed set of waveform measurements was obtained and Fig. 12 shows the chromaticities to be expected: chromaticities deduced from optical data are also shown. It will be seen that fair agreement (to within about 0·001 [*uv*] unit) is obtained in the lower half of the field. The disagreement at the top of the field noted in Fig. 11 is seen to be appreciably greater in Fig. 12. Whereas the calculated green shift is about 0·0013 [*uv*] units, the measured value is 0·0077.

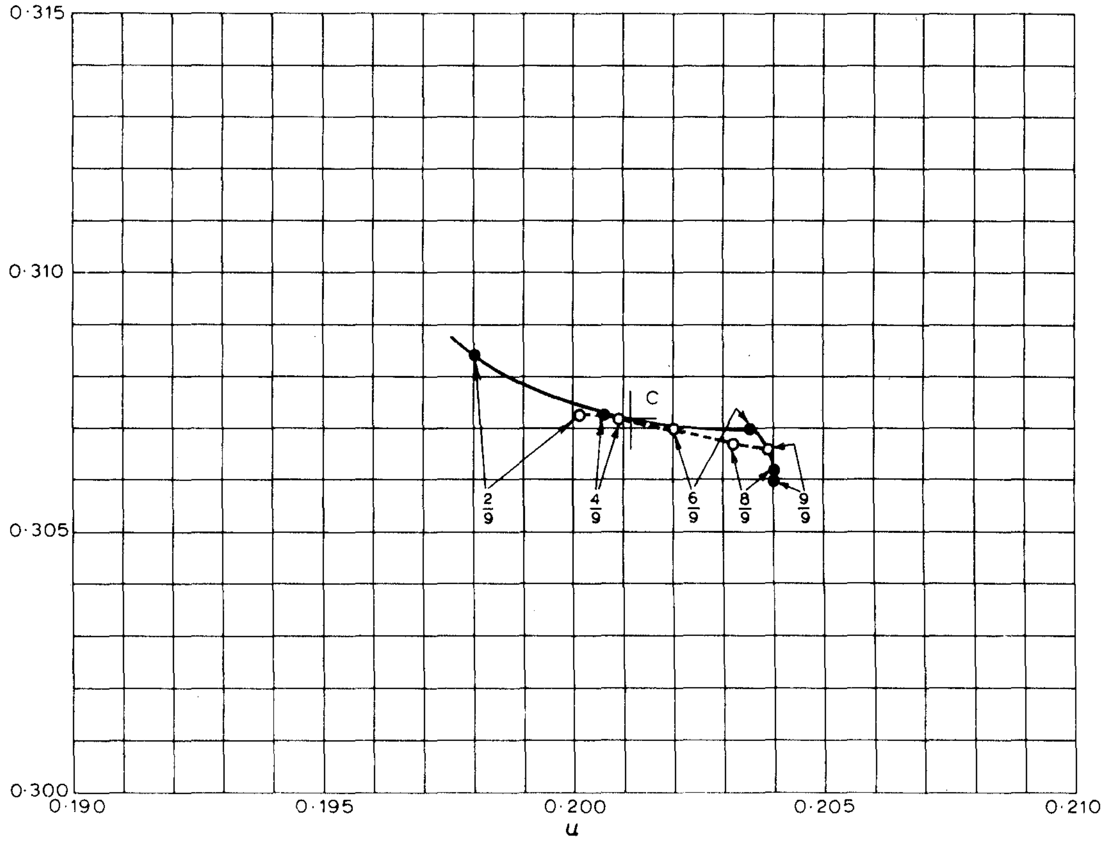


Fig. 11 - Chromaticities at stated field positions

The numbers 2/9, 4/9 etc. represent distances from top of field as a proportion of picture height

o——o——o chromaticities deduced from optical measurements
●——●——● chromaticities deduced from waveform measurements

In view of the fact that no changes were made to the camera channels or to any electronically operated part of the camera, it was considered that the increasing disagreement as the lens was stopped down must have a purely optical origin. One cause of disagreement which could operate in this way was non-uniformity of coating of the dielectric layers in the prism block. The distance between the image plane and the position of the dichroic layers is relatively small (in terms of the distance from the exit pupil plane to the image plane) so that a particular point in the image field would correspond approximately to one small area of dielectric coating. Further, this effect would become more apparent as the lens was stopped down. To test this hypothesis a further optical experiment was performed which will be described in Section 5.

As mentioned earlier in this section, the optical data can also be used to calculate the expected electrical waveforms provided that the vignetting characteristics of the Angenieux zoom lens (10 × 18E) have been measured. The zoom lens was in fact measured and a detailed comparison of the waveforms computed from optical data, with the directly measured values (Table 2) shows that fairly good agreement is achieved at full aperture but that agreement becomes progressively worse as the lens

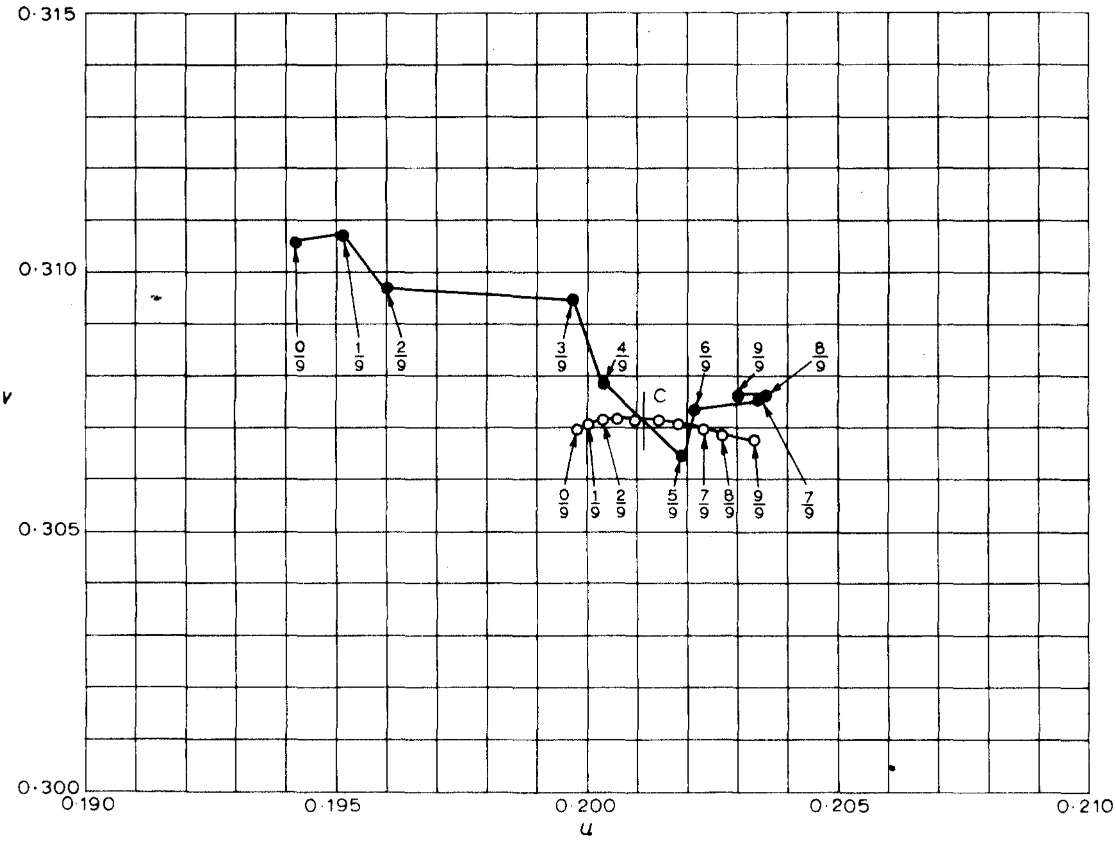


Fig. 12 - Chromaticities at stated field positions - aperture = f/16

The numbers 0/9, 1/9, 2/9, etc. indicate distance from top of field as a proportion of picture height

o——o——o chromaticities deduced from optical measurements
●——●——● chromaticities deduced from waveform measurements

is stopped down. Table 4 shows the results for f/2·2 and f/16 in the form of the ratio of the directly measured value to the one computed from optical data. This way of looking at the data confirms the observations made on chromaticity shifts (see Figs. 11 and 12); in principle it gives more information than is available from chromaticity diagrams, viz. the luminances relative to the centre of the field. As the eye appears to be quite tolerant to gradual luminance changes over the field (particularly if they are the symmetrical type associated with vignetting) the loss of information on luminance is unimportant. On the other hand, the eye appears to be very sensitive to gradual colour tilts (see Section 6) so that the computation of chromaticities is a much more critical way of looking at the results. For this reason, the full results on waveforms are not discussed in detail and Table 4 is regarded as sufficient.

5. DETERMINATION OF NON-UNIFORMITY OF COATING IN PRISM BLOCK

The agreement between chromaticities computed from optical data and those computed from waveform measurements has been shown in Section 4 to become worse as the

TABLE 4

Ratio of measured output to output computed from optical data at the various stated field positions

FIELD POSITION	0/9	1/9	2/9	3/9	4/9	5/9	6/9	7/9	8/9	9/9	CHANNEL	APERTURE
			•990		1•009		1•018		•954	•965	R	
			1•010		1•014		1•008		1•019	•993	G	f/2•2
			1•026		1•008		1•018		1•053	1•020	B	
	•827	•854	•898	•959	•987	1•013	•992	•970	•949	•897	R	
	•928	•944	•979	•979	•999	1•002	•986	•952	•936	•904	G	f/16
	•835	•852	•907	•926	•981	1•019	•980	•942	•923	•887	B	

Results normalized at centre of field (4½/9)

zoom lens was stopped down. To test the hypothesis that this was caused by non-uniformity of coating, an optical experiment was set up in which a narrow parallel beam of light was arranged to scan the prism block in a similar way to that occurring in the plumbicon colour camera when used at small apertures. For this purpose, a collimator and light source unit were arranged to pivot about a vertical axis just in front of the collimator lens and coincident with an iris disphragm simulating the exit pupil of the zoom lens. The prism block was set on the central axis of the collimator (in its undeviated position) and at an appropriate distance (180 mm) so that small beams of light came through the centre of the image apertures in the R, G and B channels of the prism block. A rotation of the collimator by just under 2° caused a shift of the light beams of 6 mm. The light fluxes in the emergent beams were measured by a photocell and opal integrator as used in routine measurements of transmission factor of lenses. From calculations based on equation 1, the variations in output due to changing angle of incidence were already known.* Any deviations from these values were considered to be due to non-uniformities in the dielectric layers. Table 5 shows the directly measured outputs and also the ones calculated from equation 1 making use of other optical data** on the same prism block. It will be observed that at a field position of 6 mm (top centre of field) the green channel is 2% in excess of the calculated value whereas both the red and blue channels are 2% deficient. This differential increase of 4% in green content produces a shift towards the green as shown in Fig. 13. Because of this, a change of •005 [uv] units from top to bottom of the field becomes •0075 [uv] units. The subjective effect of this change is considered in Section 6. Fig. 13 shows that non-uniformities give rise to an excess green component over and above that which is calculated from dichroic tilts. At the bottom of the field there is a lack of precise agreement (Table 5) but the disagreements are less than those at points corresponding to the top of the field, viz. -0•4% in R channel, +1•7% in G channel, +1•2% in B channel. The effect on the chromaticities is shown in Fig. 13. The size of beam used in this experiment corres-

* Strictly speaking, this is not quite true because the spectral response of the Sb-Cs photomultiplier is not the same as that of a plumbicon tube.

** A broader beam was used for spectrophotometry and the exit beam was approximately in the middle of the apertures in the casing of the prism block.

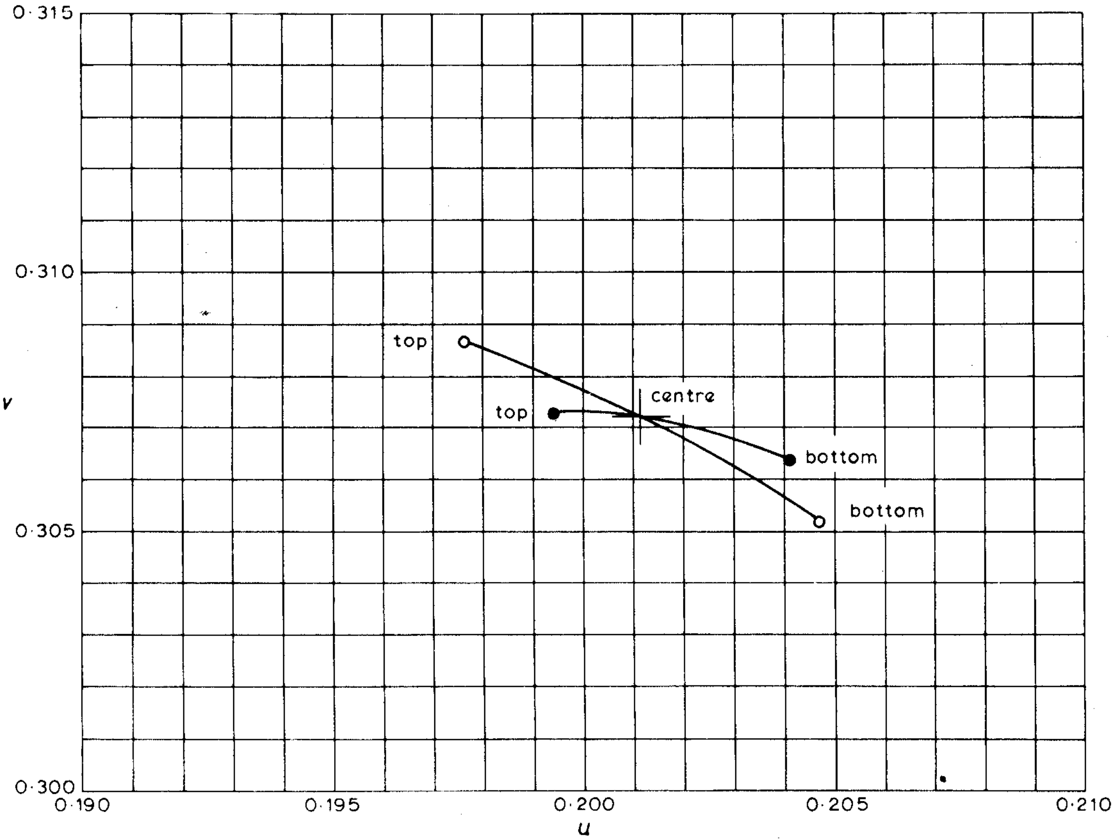


Fig. 13 - Effect of non-uniformity of coating

o——o chromaticities deduced from optical scanning experiment
●——● chromaticities assuming uniform coatings

ponded to an aperture of about f/8. It would have been preferable to use about half the beam diameter (i.e. f/16) but the loss of accuracy in measurement of the light flux made it unprofitable to reduce the beam diameter. Nevertheless, these results substantiate slight non-uniformity in the coating as the cause of the excess green at the top centre of the field.

TABLE 5

Calculated and directly observed outputs

IMAGE DISPLACEMENT	RED OBSERVED	RED CALCULATED	GREEN OBSERVED	GREEN CALCULATED	BLUE OBSERVED	BLUE CALCULATED
+ 6 mm	0·95	0·97	1·02	1·002	0·97	0·993
0	1	1	1	1	1	1
- 6 mm	1·03	1·034	0·96	0·977	1·02	1·008

6. DETERMINATION OF THE SUBJECTIVE EFFECT OF DICHROIC TILTS

Reference has already been made to units of jnd from MacAdam data.[3] The experimental arrangement used by MacAdam had a bipartite 2° field with a sharp divi-

sion between the two halves of the field. It is by no means obvious that a jnd determined in this way is relevant to dichroic tilts on a colour television monitor. A television monitor viewed at six times picture height subtends an angle of 9° × 12°. The increase in angular subtense would be expected to cause a reduction in the size of the jnd (expressed in [*uv*] units). On the other hand, the fact that the change is gradual would be expected to produce an increase in the size of the jnd. It is impossible to predict with any certainty the magnitudes of these effects: hence an experiment was set up in which tilts of the type produced by dichroic mirrors were presented to observers. In actual fact, two experiments were performed, one using a colour television monitor and the other using optical projection.

It was found rather difficult to obtain a large area of uniform white from a colour television tube without any slight changes of colour before the application of any intentional tilts. For this reason, an area of about 12 in. × 12 in. (300 × 300 mm) was masked off on a 23 in. (580 mm) shadow mask tube and over this limited area a sensibly constant colour was maintained. A colour tilt was then introduced in the line direction by application of a sawtooth waveform on to the cathode of the green gun. This was adjusted until the tilt was considered by three skilled observers to be about 'just perceptible'. By means of a photoelectric tristimulus colorimeter,[4] measurements were made on the colour near to both vertical edges of the 12 in. square patch. The magnitude of the colour difference was found to be about 0·004 [*uv*] units which is approximately the same as the MacAdam jnd from the 2° bipartite field measurements. Other more perceptible tilts were introduced to obtain an idea of how rapidly the perceptibility increases, (in terms of the 6-point impairment scale*) although this part of the experiment was not done as thoroughly as the determination of the threshold. A colour difference of 0·016 [*uv*] units (4 MacAdam jnd) was judged to be about grade 5.

Because of the difficulty of obtaining a uniform white field on a colour television monitor, an optical projection experiment was set up using two Linhof projectors. Uniformity of field was still found to be a problem and the final arrangement used only a small central portion of the total field available from the projectors. One projector gave a uniform magenta field and the other a uniform green field: both were focused on to a flashed opal screen and thus produced a uniform white field. By inserting a neutral wedge in the plane of the slide holder of either of the projectors it was possible to give the field a green-magenta tilt. The magnitude of this was adjusted until it was fairly small: fifteen observers were then invited to state whether they could see a colour tilt and if so, they were requested (a) to state its direction on the screen, (b) to name the colours observed (c) to grade the change on the 6-point impairment scale. Observers sat at a distance of six times the picture height, the screen was 10 in. × 13 in. (250 × 330 mm), no surround illumination was used (the screen was masked off by black flock paper). The luminance of the screen was about 3 ft-L. The displayed chromaticity shift was 0·004 [*uv*] units in the green-magenta direction. The mean grading of this on the 6-point impairment scale by the fifteen observers was 1·8 and the standard deviation ± 0·6

* 1. Imperceptible
2. Just perceptible
3. Definitely perceptible but not disturbing
4. Somewhat objectionable
5. Definitely objectionable
6. Unusable

grade.* Taken in conjunction with the approximate figure of grade 5 for 4 MacAdam jnd quoted above, the rate of increase of grading would appear to be approximately 1 grade per MacAdam jnd. It is estimated that grade 2 ('just perceptible') corresponds to about 1·2 jnd (MacAdam) or 0·0048 [*uv*] units. In terms of a differential change in R, G and B values this corresponds to an increase of 8% in G, relative to R and B, from the bottom to the top of the picture. For colour pictures to be free from perceptible colour tilts, the change in chromaticity must be less than 1·2 jnds (MacAdam). This is a relatively small change and considerable precision in measuring equipment is necessary to make accurate assessments.

The consequence of non-uniformity (see Section 5) in the prism block was to increase the overall colour shift from ·005 [*uv*] units to ·0075. A change from 1·25 jnds to 1·88 jnds would be expected to cause a change in subjective grading from grade 2 to grade 2·7. It would seem that if the colour tilts were due to angle of incidence effects alone, then the present plumbicon block should produce colour tilts not exceeding grade 2 ('just perceptible'). Additional colour tilt due to non-uniformity causes an increase of 0·7 grade.

7. CONCLUSION

Colour tilts in one particular plumbicon colour block have been shown to be due to two causes (a) the fundamental change in transmission/reflection characteristic with change of angle of incidence and (b) slight non-uniformities in coating of the dielectric layers which happen to add to the fundamental effect. A subjective experiment has been carried out showing that the magnitude of the 'just perceptible' colour change from top to bottom of a colour picture is only just greater than one jnd deduced from MacAdam's work with 2° bipartite fields.

The prism block system investigated is in fact remarkable for the extent to which colour tilt has been reduced although some further improvement is still required. In earlier colour cameras incorporating image orthicons, much greater tilts due to the colour splitting block passed unnoticed because they tended to be masked by shading in the tubes. The plumbicon tube is virtually free from shading.

8. RECOMMENDATION

It is recommended that a specification for a colour television camera should include the following clause:

> 'For any value of the main lens aperture between f/11 and the maximum, the change in colour analysis characteristics due to changes in the angle of incidence with change of field position shall be such that the ratios of the largest to the smallest linear R, G and B signals (assuming camera tubes with uniform sensitivity over their photosurfaces) corresponding to a uniform white field (which have been normalised to unity at the centre of the field) shall not exceed 1·04 at the top centre and bottom centre of the picture, or at the edge of zone 2[5] whichever is relevant. Furthermore, changing the aperture of the main lens from f/11 to the maximum shall not cause changes greater than ± 2% in the relative values of the R, G and B signals corresponding to the centre of the field.'

* Standard error was ± 0·15 grade.

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